Radar the Next Generation - Sensors as Robots

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Abstract—**One can easily envision future military operations and emerging civilian requirements (e.g. intelligent unmanned vehicles for urban warfare, intelligent manufacturing plants) that will be both complex and stressing and will demand innovative sensors and sensor configurations. The goal of our research into Sensors as Robots is to develop a cost effective and extendable approach for providing surveillance for a variety of applications in dynamically changing military and civilian environments. Within Sensors as Robots, we foresee a new sensor archetype. In this paradigm, sensors and algorithms will be autonomously altered depending on the environment. Radars will use the same returns to perform detection and discrimination, to adjust the platform flight path and change mission priorities. The sensors will dynamically and automatically change waveform parameters to accomplish these goals. Disparate sensors will communicate and share data and instructions in real-time. Intelligent sensor systems will operate within and between sensor platforms such that the integration of multiple sensor data provides information needed to achieve dynamic goals and avoid electromagnetic fratricide. Intelligent sensor platforms working in partnership will increase information flow, minimize ambiguities, and dynamically change multiple sensors' operations based upon a changing environment. Concomitant with the current emphasis on more flexible defense structures, Sensors as Robots will allow the appropriate incremental application of remote sensing assets by matching resources to the situation at hand.**

In this paper, we discuss the development of a futuristic intelligence, surveillance and reconnaissance concept utilizing the innovative integration of cutting edge technologies such as: knowledge-based signal processing, robotics, wireless networking, waveform diversity, the Semantic Web, advanced computer architectures and supporting software languages. This concept is projected as an autonomous constellation of air, space, and ground vehicles that would offer a robust paradigm to build toward future deployments.

I. THE CONFLUENCE OF FACTORS

Currently, many national defense institutions are undertaking major alterations in their capabilities, from forces designed during the Cold War to those adapted to 21st century adversaries including terrorism. This change has been driven by a changing threat as well as technology innovations, especially information technology. As the military services attempt to increase the agility and versatility of their forces, they also see a need to increase the capabilities of military intelligence, surveillance and reconnaissance (ISR) to support the new weapon systems and operating methods against these new threats. Intelligence, surveillance, and reconnaissance refer to efforts to collect information and use it in militarily significant ways[1].

Based on changes in both the threat and in available technology, national defense organizations either are in the midst of, or recognize the need to "transform".[2] Transformation in the context of large organizations is generally recognized as a process of radical change involving technology, organization, and concepts of employment. Another expression used in military terminology that also expresses the idea of transformation is "revolution in military affairs". There are at least two competing perspectives on what constitutes "transformation." To some, transformation is characterized as a discontinuous or leap-ahead change.[3] This view supports those who believe it is necessary to move money, manpower, and particularly patterns of thinking ("doctrine") away from current weapon systems and methods, to entirely new technologies and procedures. They perceive that resources are being wasted on the older systems, and the only way to accomplish change is to do so in a radical way. The United States Navy's shift in the 1920s and 30s from the battleship to the aircraft carrier as its centerpiece weapon system could be considered an example of a leap-ahead change, even as the battleship remained in service until the 1980s. The US Army's plan to replace its tank force in favor of much lighter vehicles and other technologies may be seen as an attempt to achieve similar change.[4]

Others tend to classify transformation as incremental change using current technologies in new ways, with an end result of far-reaching improvement over time. They express concern that the future is unknown; if proven capabilities are eliminated for new ones, those new capabilities may not address the currently unforeseen threat any better than today's technology. A proven technology, however, may be able to be adjusted to meet that unknown situation.

Whatever one's position is, we believe that the Sensors as Robots program is in harmony with the broad idea of transformation. By innovative integration of cutting edge technologies, the Sensors as Robots program will be focused on developing the system-level concepts to enable autonomous and agile ISR operations.

II. MOTIVATION

A Boy Scout troop is charged with cleaning the town park. Initially, each boy is assigned a specific task and timeline. However, soon into the exercise, and as a result of some minor and perhaps major situational changes, the original individual marching orders are modified, or perhaps even ignored, on the fly. In any event, however, each member of the troop does his part to accomplish the goal of cleaning the park. In the end, the mission is successfully completed. Independent entities (the Scouts) have operated in an autonomous manner using cognitive reasoning in responding

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14. ABSTRACT

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to real-time changes in the environment, to accomplish a pre-assigned mission. The individual Scouts, by sensing the behavior and activities of their colleagues in response to the changing environment, and by communicating the necessary data and information, achieved a collective response that resulted in a "successful" operation. This "system" worked as a result of the autonomous and intelligent interaction between the individual "subsystems".

Imagine it is the year 2013 and friendly sensor assets are hovering over the enemy fighter aircraft as shown in figure 1. This scene could be taking place today. However what this
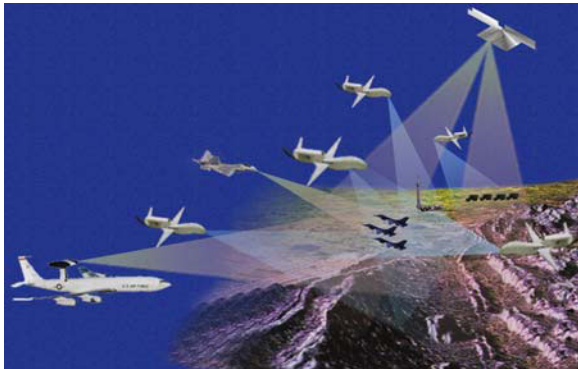

Figure 1. Futuristic Scenario

figure does not show is that each sensor is performing independently as they are today and in concert with all other sensors, similar to our Boy Scouts. Each sensor is autonomous trying to meet their independent goals (e.g. surveillance, imaging, tracking, etc.) but are working in concert providing and receiving data and information from near and distant sensors that help them in achieving their goals and assisting other sensors to achieve theirs. Each sensor system will have intelligent software within their processing system that can manage its resources, communicate with other sensor systems, provide data/information, and fulfill requests from other sensors and human operators.

Consider the following scenario where a radar is going to drop track due to an obstruction from a mountain. Previous communications and sharing of data/information has occurred such that this radar only needs to send a small encoded message to all nearby sensor platforms in advance stating that if track X continues in its present direction the radar will lose the target because of an obstruction. Another sensor platform will accept the primary responsibility for tracking the target based upon set criteria established within their intelligent system software, confirms the track takeover, and reports the results to the user. In the interim, both sensors will track the target, share their raw data, and using stereo processing and imaging, they will pinpoint exactly where the target is located and identify it with minimum error; all performed without human intervention.

There will be multiple levels of intelligent processing performed throughout, for the sharing of data and information between sensors on manned and unmanned platforms, between platforms, between combat areas, and between command centers. Missions and goals will change in real-time at all levels (i.e. sensor, platform, combat area, etc.) and sensors will be tasked to change accordingly, whether it is to

detect targets, track them, help identify targets with other sensors, perform battle damage assessment, or guide weapons to a target. Sensors are resources that will act independently but in concert as global goals and missions change in real-time to meet requirements in a changing environment. Placing intelligence within sensors and sensor platforms will allow them to adapt in a more dynamic and cooperative manner just as we deploy and task our combat forces. To meet these goals we must put intelligence, communications, robustness, and variability (e.g. waveform diversity) within each of our sensor systems, and leverage a variety of technologies. Sensors as Robots is a goal oriented concept that is in stark contrast to "stove pipe" systems currently deployed. We need a concept, to motivate and direct our research and development, which is larger than an autonomous vehicle with sensors onboard. Intelligent software processing is required at all stages of signal, data, and system processing from the filtering, detection, tracking, imaging, and identification stages to guiding of weapons to a target, battle damage assessment, communications, command, and control.

Contemporary radar sensors and systems in general are not optimally integrated within the platform on which they reside. They do not adequately share nor receive information from other systems on the same platform, or between platforms. Sensor platforms, for the most part, are a heterogeneous collection of disjointed sensors. However, the intelligent integration of multiple sensor data sets could create valuable information for improved overall mission performance. The user community is data rich and information poor when it comes to raw data from sensor systems. Consistent with the Sensors as Robots theme, it will be important to have sensor systems automatically share data and information so that their composite result provides maximally useful information to the user.

Historically, radar systems have been built given a fixed set of requirements. As a result, bounds on operational flexibility have been set. Imbedded processing algorithms were derived under assumptions that may not always be valid. As a result, these algorithms may not be well matched to modern-day needs. Most radar sensor systems operate stand-alone and do not communicate with other systems except for handoff, and generally perform single mode operations. In the future, simultaneous multi-mission multi-mode operation will be required.

Current fielded radar system software is difficult and costly to change or port to new processors since it is often computer platform dependent. However, there are efforts underway to minimize the effort of porting software to different architectures. One effort's approach developed a compiler that will input MATLAB code and generate efficient low level code that will run on a distributed environment of commercial off the shelf hardware of field programmable gate arrays (FPGAs). This approach evolved from research funded by the Defense Advanced Research Project Agency (DARPA). The reader is referred to http://www.ece.northwestern.edu/cpdc/Match/Match.html for more information. Another approach (also partially funded by DARPA) is being pursued by a consortium called the VSIP Forum. They are developing a Vector Scalar Image Processing (VSIP) Library (VSIPL) (www.vsipl.org). The VSIPL primitives are low level and are currently written in C. The Core profile contains 515 functions and Core Lite

contains 125 of these same functions. Both Mercury and Sky Computers, two builders of special purpose architectures for signal processing, support VISIPL functions. A third approach funded by the US Air Force and US Missile Defense Agency is investigating the benefits of converting MATLAB code to Java, C, C++, and to VSIPL primitives. (Unpublished final report for USAF contract F30602-99-C-0141). Pursuing these and other approaches will help meet the demands of lowering the cost of software development and portability.

Sensors as Robots foresees a new sensor archetype. In this paradigm, sensors and algorithms will be autonomously changed depending on the environment. Radars will use the same returns to perform detection and discrimination, and provide data to alter the platform flight path and change mission priorities. The sensors will dynamically and automatically change waveform parameters to accomplish these goals. Dissimilar sensors will communicate and share data and instructions in real-time. Intelligent sensor systems will exist within and between sensor platforms such that the integration of multiple sensor data will provide information needed to achieve dynamic goals and avoid electromagnetic fratricide. Intelligent sensor platforms working together will increase information flow, minimize ambiguities, and alter operations based upon a changing environment. Consistent with the current emphasis on a more flexible defense structure, Sensors as Robots will enable the incremental application of remote sensing assets by matching appropriate resources to the problem.

The targeted application for Sensors as Robots is the Unmanned Airborne Vehicle, (UAV). In the regime of UAV-based remote sensing, we envision the ability to detect and exploit observable phenomena in the "*Long, mid and near*" range by mimicking the integrated use of the five natural senses plus memory and exploiting our understanding of human, animal and insect behavior for deployment and operation. Improved sensor signal and data processing will be gained from knowledge based and "a priori" information, multiple processing paradigms, and sensor fusion. Through the use of all available sensor and control data, autonomous maneuvering (locomotion, displacement and "right" placement) of UAV sensors can be achieved. UAV based sensors will have to accomplish difficult tasks in dynamic environments. However, existing robotic systems accomplish simple tasks that are not scenario level functions and they generally do not operate in concert with other systems. While some multi-function robotic systems exist, (factory "system of systems"), they are operating in carefully controlled environments. This research initiative will strive to meet future UAV sensor requirements to perform multi-level autonomous functions dynamically, in the real world.

Future military and civilian requirements will be stressing and will require innovative sensors and sensor configurations. However, many on-going and promising research and development investigations increase our confidence that maturing technologies will foster success. Examples which will augment Sensors as Robots and advances in UAVs include the development of knowledge based space time adaptive processing (KBSTAP)[5,6] a dynamic software architecture for the filtering, detection, and tracking stages of radar processing, using the "non-homogeneity detector"; United States Geological Service (USGS) "map" data[7];

archival radar data; as well as off board sensor data to select the most appropriate space time adaptive processing (STAP) training data for improvements in filtering, detection, track, identification and handoff; as well as waveform selection and flight planning. As a result of recent and current research efforts, well-grounded and validated signal processing algorithms[8,9] abound. To deal with the enormous quantity of data expected in the future system architectures, increased processor speeds will be needed. On-going industrial activities are resulting in processor speeds that are doubling every 18 months. At the same time, the object oriented software paradigm is helping to reduce the cost of software via software reuse. The next generation Internet and the AI (Artificial Intelligence) communities are providing new software tools and models as well that should prove to be useful in this initiative.

The confluence of on-going research objectives can be built upon as we move towards a future "Sensors as Robots" configuration. For example consider the Autonomous Navigation and Sensing Experimental Research (ANSER) program executed by BAE Systems Australia and the University of Sydney's Australian Centre for Field Robots. In these experiments, the goal was to demonstrate decentralized, multiple UAV tactical-picture compilation of ground targets. Communications equipment was used to permit direct UAV-to-UAV WLAN and remotely piloted flights over a test range in New South Wales were conducted. Building on the tremendous success of programs such as ANSER, one of our goals is to eliminate the need for remote piloting so that the Sensor as Robots function with only initial instructions and the ability to reconfigure flight paths autonomously as the mission unfolds. Clearly the initial success of Remotely Piloted Vehicle programs are essential to the incremental progress that will lead to a true "Sensors as Robots" manifestation.

Eventually, technology will permit the deployment of multiple UAV platforms in performing dynamic scenarios. Each UAV could have a suite of heterogeneous sensors that can operate autonomously or in concert with other platforms. In this manner we can deploy the correct number and type of UAVs to meet the requirements and goals of the deployment, reduce risk, and minimize the use of expensive or manned platforms. Sensors as Robots technology will help to accelerate this process for both military and civilian applications.

III. AN INTELLIGENT SENSOR SYSTEM

In order for a system of sensors platform to share and receive information from multiple sources, it must be able to communicate and understand the information. A potentially powerful solution for the exchange of information between heterogeneous sensors is for each sensor to publish information based upon an accepted and understood format (i.e. ontology). In this manner when a sensor publishes its track data, for example, other sensors receiving this information will be able to interpret its contents without ambiguity. Achieving this will require that certain basics be established. There must be available an accepted method of defining the Earth's geometry such that the location of every element is defined within the same coordinate system and that each element is time synchronized with the same clock and all communications are time stamped.

Each transmission of information between sensors must describe its time and coordinates. In addition, if it is sharing track or target data, it must specify a unique identifier, the sensor platform's velocity, pitch, yaw, and roll and Meta data describing the transmitted raw data along with encryption/decryption keys. The unique identifier will allow the receiving sensor to acquire, within its resident database management system, all of the sender's radar characteristics. Sensor characteristics include such things as nomenclature, power output, bandwidth, frequency, antenna pattern, pulse width, pulse repetition frequency, etc., as well as platform characteristics as to the position of the antenna on the platform, number of elements, the pattern of the elements, the pointing vector of the sensor, etc. An ontology is needed for defining these data and numerous rules such that the information published by any sensor can be understood correctly by the receiving sensor to perform functions such as sensor fusion, track correlation, and target identification.

Sharing information between sensors on the same platform is also required, especially if one or more sensors are adaptively changing waveform parameters to meet the demands of a changing environment. Figure 2 depicts a notional intelligent sensor system. Each of the sensors has its own signal and data processing functional capability. In addition to this capability, an intelligent processor to address fusion between sensors, communication between sensors, and control of the sensors has been added. A primary goal is to be able to build this processor such that it can interface with any sensor and communicate with the other sensors using ontological descriptions via the intelligent platform network. The intelligent network will be able to coordinate the communications between the sensors onboard and to off platform sensor systems. There are approaches that can be exploited to build this system by using fiber optic or wire links onboard the platform. Radio frequency (RF) links using Bluetooth or 802.11 technologies can be utilized for linking these sensors onboard the platform. Between platforms, other technologies may be implemented such as mobile Internet protocol over RF communications links. The communications issues need to be addressed for the sharing of information and for minimizing the potential of electromagnetic (EM) fratricide. The intelligent platform should determine, for example, if there is EM interference (EMI) potential when a sensor's antenna's main beam pointing vector or PRF is changed, and may thereby cause interference to a receiving sensor. Rather than have each sensor on a platform operate as an independent system, platforms would be designed as a system of sensors with multiple goals managed by an intelligent platform network that can manage the dynamics of each sensor to meet the common goal(s) of the platform.
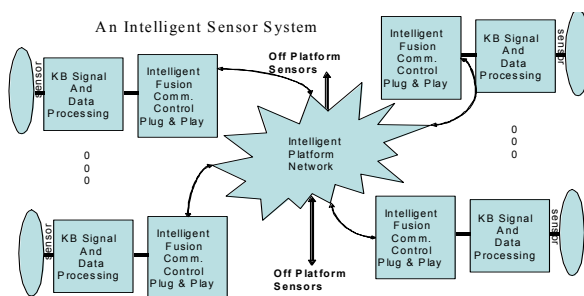

Figure 2. An Intelligent Sensor System

IV. COMPONENT BUILDING BLOCKS

In order to be successful, the Sensors as Robots program must leverage, and in some cases, stimulate advances in an array of technological regimes. These include:

- Sensor systems and signal processing research activities to develop knowledge-aided sensor signal processing techniques to maximize the use of prior knowledge in radar signal & data processing for improvements in detection, track, identification & handoff; state-of-the-art facilities such as the US Air Force Research Lab Signal Processing Evaluation, Analysis, and Research (SPEAR) facility for the evaluation of signal processing algorithms; and technology and software for integrating, managing, and sharing information between multiple sensors and information resources.

- Language/model development for numerical and non-numerical processing efforts and activities will be required to provide the capability to easily define the signal, data, and logic based sensor-processing functions. Requirements will include the capability to exercise this language on conventional processors for emulation and evaluation of single and multiple sensor sub-subsystems where their respective information for all sensors' use is fused. Research and development activity will be required to develop the capability to store and access multiple dynamic and stable data and information sources as well as the ability to model the processing within and between multiple sensors and communications systems.

- Artificial intelligence (AI) – robotics programs will be critical to the Sensors as Robots program by leveraging, for example, the work of the World Wide Web Consortium (W3C) and activities such as the Defense Advanced Research Project Agency's (DARPA) Agent Markup Language (DAML) program, which will lead to the next generation Internet or the Semantic Web. The Semantic Web will allow one to develop Web pages that are written such that software can read and understand their contents. The next generation Web is being designed in a manner similar to a large knowledge base such that one can define ontologies for different domains of interest (e.g., radar or sensors). The concept of ontology is exactly what is needed to achieve a system of sensors that operate in a collaborative fashion and eventually, to have sensor platforms operate autonomously as a robotic system. In order to operate cooperatively they must be able to communicate, share data and information, and understand each other and their environment. Leveraging the approach and technology of the W3C will allow for the development of ontology for sensors thereby having one knowledge base that can be understood by all new knowledge based sensor systems added to the overall domain including communications, radar, electro-optical, infrared, acoustic, etc. This approach will allow multiple sensors on one platform to inference and fuse data and information from all sensors on board. It will also allow for this platform to share and fuse data and information between sensors on multiple

platforms located nearby or at a distance within a command center. The construction of ontologies is a present-day activity. They can easily be found on the Web and can be used to build and share information within the community and domain of interest. The Sensors As Robots program will leverage the object oriented feature of inheritance and reference the resource descriptive framework (RDF) (i.e. an instantiation of an ontology) of those ontologies that already exist and then add those additional facts and rules required for one's own needs. For example, if an RDF describing facts and rules for a transmitter, a receiver, and an antenna already exists, and the facts and rules meet ones needs, then they should be referenced in the radar ontology that one is building as opposed to building anew. Ultimately, it will be possible to develop the AI algorithms and processing rules within various sensor types such as radar, electro-optical, acoustic, infrared and perform multiple tasks such as imaging, detection, tracking, target identification and to develop ontologies for multiple sensor types and communication systems so that they can exchange data and information in a coherent and timely fashion.

- Waveform diversity encompasses both the adaptation of waveforms in order to compensate for the environment and multi-user interference, as well as receiver structures that employ *a priori* and estimated knowledge to separate desired information from multiple users and jamming. Effort will be needed to investigate waveform diversity techniques that enhance the performance of multiple sensor types. Research efforts to develop algorithms and procedures to alleviate fratricide issues related to dynamic frequency assignment in and between moving and fixed platforms must be undertaken. Development of communication protocols and techniques to maintain communications while dynamically changing waveform parameters will be needed.

- Communication models and procedures to develop fault tolerant techniques for the multiple sensors and communication devices to communicate within a platform will be required. Similarly, fault tolerant methodologies for multiple platforms to communicate by leveraging different commercial protocols such as Bluetooth, 802.11, and mobile IP are needed. These technologies will be the bond that connects supporting technologies such as operations planning, mission planning, reasoning, decision making and distributed real-time computing and control. The development of wideband communications technologies to be used between platforms to transmit and receive large amounts of data such as data cubes and their proper ontological header data, in real time will be essential.

- Software development activities to leverage languages such as MATLAB and the results of language/model development efforts to create a library of algorithms will be needed. Efforts to develop techniques and tools to automatically map these language characterizations to different computer architectures (and their languages, Java, VSIP, C++) must be initiated. On-going activities to develop methods to

minimize the cost to maintain and upgrade software on fielded systems will be watched closely and used as needed.

- Computer architectures research efforts to develop fault tolerant computer architectures that can process signal, data, and logic/control of a real time sensor system are needed. Effort to develop architectures able to accommodate both numerical and non-numerical processing and be able to store and retrieve large amounts of data describing such entities as ground truth, map data, intelligence data, battle damage assessments will be required. Programs to acquire architectures able to process multiple tasks in parallel with the same sensor data (e.g. tracking and imaging), and be able to spawn off multiple task instantiations of each with different algorithms for comparisons in real time as the environment changes must be started. In addition, architectures able to receive data, information, and control from multiple on board and off board sources such as communications links and other sensors will be essential.

Other technological advances such as robotic locomotion, wireless networking, detection and classification algorithms for multi-modal inverse problems, etc. will be closely monitored as well, and where appropriate, leveraged into the overall Sensors as Robots program.

V. INITIAL DIRECTION

The development of the Sensors as Robots concept will proceed using a top down systems level methodology in which advances in the COMPONENT BUILDING BLOCKS above are utilized and integrated. For example we would incorporate embedded AI and software advancements, leverage Semantic Web technologies (i.e. XML, ontologies,…), employ intelligent sensor and platform management algorithms, capitalize on ultra wideband, optical, and wireless advancements (e.g. mobile IP, 802.11, Bluetooth), and use human engineering interface control for intelligent sensor systems.

The system strategy that will be employed in the Sensors As Robots program is basically a three-phase approach (Figure 3): (1) development of a baseline Sensors As Robots prototype utilizing state-of-the art Component Building Blocks (Version 1.0); (2) Periodic Upgrade and integration of advancements in Component Building Blocks (Version 1.1, Version 1.2, etc.); (3) Release of an approved version to the appropriate sponsor for implementation. This phased approach will be iterated in a spiral fashion as knowledge, technologies, and approaches mature.
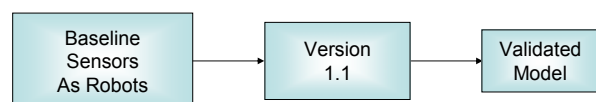

Figure 3. Sensors as Robots Methodology

An objective of the Sensors as Robots approach is to accelerate and facilitate application of mature advanced technologies (the Component Building Blocks) to assist in the

development of a cognitive autonomous sensor system and thereby provide new operational capabilities that will make a difference in military and civilian applications. At this point, the process by which a Sensors as Robots candidate moves from the initial phase to a validated model is very flexible but might typically be described as follows.

The baseline form of a Sensors as Robots implementation will be represented by a collection of technology programs that are combined and integrated into a demonstration carried out in the laboratory to develop or enhance a military capability or a needed civilian application. Generically, this implies identifying significant operational shortfalls, matching them up with technology programs ready to focus on important applications, and responding to a user-sponsor who believes that application is important to his mission. The result of a phase 1 effort will be a Sensors as Robots system comprised of the most mature technology building blocks available and will be labeled Version 1.0. It will, however, be just a starting point. Version 1.0 will embody a rudimentary autonomous system; however, it will serve as a demonstration platform as we build towards a more sophisticated system.

As technology advances are achieved in the Component Building Blocks, judicious selection and integration of these advances will be inserted during phase 2 and the Sensors as Robots model upgraded to Version 1.1, 1.2, etc. During this phase, each version will meet certain criteria with respect to interoperability, functional performance, robustness, etc. At some stage, when a certain level of specified performance is achieved, the Sensors as Robots model is released as Version 2.0. Of course this model must be thoroughly coordinated with potential sponsors throughout its development phases.

In this manner, and as the methodology is refined, the Sensors as Robots program will provide a mechanism for achieving a cognitive, autonomous sensor system.

VI. SUMMARY

In future scenarios, unattended air and ground based sensors will be called upon to accomplish difficult tasks in dynamic environments. For example, we foresee military applications in the vein of the surveillance of hostile urban battlefield situations as well as monitoring functions inherent to peacekeeping activities; civilian applications such as crop production assessment/management and traffic assessment/management; industrial applications that include factory smoke emissions monitoring, production assembly assessment and management, facility management, and inventory shipment and tracking.

However, existing UAVs and mobile robotic systems can only accomplish straightforward or repetitive tasks which are not scenario level functions and they generally do not operate in concert with other systems. More will be needed in the future. Propelled by the twin factors of transformation in military affairs and the dramatic increase in technological innovation, we believe that the environment is right for the introduction of a new concept in sensor system technology. This concept would embody cognitive, autonomous sensor system operation where the types and numbers of sensors would be matched to the task at hand. Sensors will collaborate with each other by sharing information, sensing the environment, adapting operation as necessary, and will do

this by incorporating artificial intelligence, capitalizing on advancements in the Semantic Web, employing intelligent sensor & platform management algorithms, exploiting ultra-wide band communication, optical, & wireless advancements and by utilizing human engineering interface control for intelligent sensor systems.

The Sensors as Robots initiative is a forward looking initiative that we believe will act as a catalyst and vehicle for stimulating the developments needed to make such future sensor systems possible.

VII. APPENDIX A: ROBOTIC FUNDAMENTALS[10]

The word robot was derived from the Czech word for forced labor by Karal Capek in R.U.R (Rossum's Universal Robots), published in 1921. The modern definition of a robot classifies it as a machine with these features: an algorithm for instruction, moving parts for action, sensors to discern items of interest from everything else, a process to select appropriate actions, and a controller to govern overall operations.

A major focus of the robotics industry is manipulation, i.e. the arm and hand action required for automation of the manufacturing process. Most important among these are the revolute and prismatic joint, the rectangular, cylindrical, spherical, and articulated arm. The industrial robot hand, multi-fingered with force-sensing wrist, compliments the joints and arms described above. Mobile ground based robotic systems require legs and feet, or wheels/tracks. Airborne robots and underwater equivalents require more sophisticated mechanisms for locomotion. A mobile robot must also have a navigation system. In primitive short range robotic systems, dead reckoning is adequate. Today, electronic signals such as GPS (global positioning system) aid in long range navigation. This is especially important in air and space craft.

Robots may incorporate sensors that imitate the senses. In the animal kingdom, stereo vision and the visual cortex enable image formation and analysis. In robots, passive and active electromagnetic sensors may function in this capacity, albeit not to the level of human expectations. Force and torque sensors are routinely implemented using strain gauges in robotic systems. Acoustic, scent, and heat sensors are also readily available. Integration, as in the human brain, requires work on several problems simultaneously, akin to parallel processing. Humans also think on several levels at once, thus establishing a hierarchy. This is also of interest in robotic research.

Teaching a robot is also a challenge. Among the simplest to teach are fixed stop robots used for pick-and-place operation. In servo-controlled robots, learning may be more difficult. A servomechanism is a device that knows where a machine is and should be in its environment. This permits the controller to compare where the machine should be and how to get it there. There are many ways to teach a servo-controlled robot. In one approach, a human can guide a robot through its various motions, recording position and time information. Alternatively, robots may be programmed using computer languages specially designed to describe motion and angles. One popular industrial method combines these techniques.

Intelligent teleoperated systems may have limited computerized control. With supervision, an onboard computer may makes decisions, or an operator can take control of the process.

All of this begs an important question, "Why aren't there more robots in the work place?" Two problems impede progress. Robots are not accurate enough and need greater intelligence. When the human brain is compared to computers, it is the more complex among any man made device. Symbolic processing is a small part of how the brain works. Humans also have associative memory and the brain stores information in such a way that limited words or images can evoke memory of a complicated series of events. Robots will require this level of sophistication in future work place environments.

Humans understand structure, can plan to solve a problem, and then carry it out, adapting along the way. The brain doesn't store information about simple tasks or other knowledge all by itself. Information is stored within the context of events and ideas. Also, a person can apply the knowledge learned about one situation to another. This type of learning is called generalization. Even the simplest task involving generalization may be well beyond the capability of modern computers or robotic systems. As a result, we use expert systems to mimic human behavior, in order to facilitate the robotic process.

In computers, expert systems are programs that follow a menu or recipe. Each one contains a body of information, a method of collecting specific data concerning a problem under consideration, a set of rules to process the data, and a set of instructions for taking action.

A domain expert has two types of knowledge. One type is data about the problem of interest. The other focuses on method of using that data. A general description of the problem and data is inadequate. The expert system must include operations that may be performed automatically on the data, and the ability to reason and adapt to unexpected conditions. Reasoning includes the ability to translate experience into rules. This is shallow or heuristic reasoning. Deep reasoning is concerned with analyzing a problem to discover its basic structure. Both kinds are used by experts.

Significant research currently focuses on teleoperations and sensor improvements. Sensors as Robots will require the transmission of more realistic information to their human colleagues – what is called telepresence. This may require artificially intelligent robots. An intelligent robot still needs a plan to follow. The plan should include intermediate goals. It should also be able to deal with failures and – most of all – the unexpected. The robot also has to learn from its experiences. And it has to be aware of what it knows and doesn't know.

The most important skill an intelligent robot will need is introspection, the ability contemplate its method of reasoning. Introspection will enable computers to distinguish between what it knows and what it needs to learn. In a dynamically changing environment, this will permit robots to decide whether to act or to pursue additional information.

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